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Human Systems Program

Dynamics of the Eye and Head During Movement Between Displays: A Qualitative and Quantitative Guide for Designers

by

Gordon H. Robinson

~~January~~ 1978 Tech Rep TR-78-2

Department of Industrial Engineering
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Dynamics of the Eye and Head During Movement Between Displays: A Qualitative and Quantitative Guide for Designers

GORDON H. ROBINSON, Dept. of Industrial Engineering, University of Wisconsin, Madison.

ABSTRACT

The purpose of this paper is to provide a designer or systems analyst a guide to human performance limitations in vision when fixation must be redirected from one display to another. The focus is on large angular separation (greater than 20 degrees) and on tasks wherein speed is of importance. Patterns of eye and head movements are shown; as well as quantitative data on saccades, periods of eye/head compensation, and head movement. Independent variables include inter-display angle, display visibility, operator's knowledge of display location, and some relevant characteristics of a possible task which must be interrupted for the refixation. Inter and intra subject variability is also presented.

INTRODUCTION AND SETTING

This paper describes the dynamics of the eye and head as vision is redirected from one fixation point to another. The purposc is to provide a qualitative framework and quantitative performance data that will assist a designer in predicting operator performance in tasks requiring such refixations. Common tasks include monitoring large instrument panels and controlling complex vehicles. The data here will probably be of most interest in "speeded" tasks, where fractions of a second may be important, and with those displays separated by larger angles (20 degrees or more). Perhaps the most universally appreciated example, in the US at least, would be the visual dynamics involved when driving an automobile and merging from an on-ramp onto a busy freeway. The time required here to move visual fixation from ahead, back to a possible traffic gap, and to return will often exceed the time gap to the vehicle ahead.

SCOPE

Each visual refixation involves a decision to leave the original display, programming the initial movements of the eye and possibly head, neural and muscular reaction times, the pattern of eye and head movements necessary to acquire the new display, and the subsequent processing of the new display. Many tasks, such as vehicle control, also require the rapid return of fixation to the first display, where it may provide information used in continuous control.

This paper will not concern itself with the decision to seek the second display nor the information processing that may go on after it has been acquired. It will be concerned with the total pattern of eye and head movements that follow such a decision and and with visual acquisition of the second display. This decoupling of these three phases seems theoretically reasonable and has been demonstrated in the laboratory (Robinson, Koth, and Ringenbach, 1976).

The paper will also indicate, in as quantitative a manner as possible, the effects of common systems variables including display spacing and visibility, operator's prior knowledge of display location, and characteristics of the initial display which affect the dynamic pattern. An approximation of the range of individual differences and intra-person variability will be given, where known.

SOME RELEVANT FEATURES OF THE EYE

It is useful to have a rough model of the eye in mind when attempting to use the ideas and data to be presented. Some important features will be presented briefly. (Numerous books are available on the general anatomical and physiological features of the human eye if the reader wants a more complete picture.)

The important feature of the human eye is the relatively small angular region within which there is useful visual acuity. This property derives from the function and spatial distribution of the two photoreceptors found in the eye. The "cones," responsible for acuity (detail) and color perception are located as shown in figure 1.

The "rods" are distributed outside the dense cone area and are responsible for detection of peripheral displays of interest which may then be acquired by the cone region (fovea) for detailed perception.

The resulting central (foveal) angle through which practical processing can occur is related to target size, brightness, and contrast. Commonly presented acuity data can be misleading here in that it is reflective of minimal, threshold conditions and is difficult to relate to displays of size and visibility in common use. Figure 1 illustrates this issue, showing both an acuity function and illustrative data on readability of a common digital display. Note, for example, that this specific display would be correctly identified at greater than a 50 percent level up to 40 degrees from the fovea.

In most situations fixation is close to the item being processed, usually within 2 or 3 degrees. It must be anticipated, however, that if time is of importance the operator may process the visual data with a fixation point that can be as much as 10 degrees from a highly visible display. This descrepancy will assist in speeding return to the original display.

Visual redirection is accomplished by coordinated movements of the eyes and by movements of the head and body if necessary. Four control systems for eye movement have been identified, corresponding to: 1) rapid movement to acquire a new display--saccadic movement; 2) slower, pursuit movement to follow a moving display; 3) opposed movements of the two eyes to focus on objects at close range; and 4) compensatory movements of the eyes equal and opposite to head movements to maintain stationary fixation for visual perception during head movement. (Discussion of dynamic properties of these four systems can be found in Robinson, D. A., 1968). Concern here will be with movements between stationary displays at approximately equal depths and therefore with the use of systems "1" and "4" only.

It is generally agreed that little if any visual processing occurs during a saccade, although the mechanism for this suppression is not yet clear. (Matin, 1974 provides a review and discussion of this issue.) Visual processing can and does take place during the eye/head compensation movements (Data and discussions of this issue appear in London, Nelson and Robinson, 1978 and in Bartz, 1978.)

Movement of the head, necessary for visual redirection beyond about 40 degrees, has not been studied extensively. Most eye movement research has fixed the head to allow more precise eye measurement. Care must be taken when applying these data in real-life situations where the head is free to move. The initial eye/head compensation patterns to be discussed in the Reaction Time section and occasionally reported overshoots of saccadic movements are both qualitatively different whether the head is free or not. In fact, it is reasonably easy to inhibit head movement by instruction and care must therefore be taken in laboratory measurements if they are to be extrapolated to normal, free head situations. (Bizzi, 1974 and Robinson, Koth, and Ringenbach, 1976 discuss eye/head coordination data.)

DYNAMIC PATTERNS OF EYE AND HEAD MOVEMENT

Two distinct time periods appear in the dynamic patterns of eye and head movement during wide angle refixation: 1) a reaction time (latency) between the command to refixate and the first movement of the eye and 2) an interval containing saccades, head movement, and eye/head compensatory movements leading to visual acquisition of the new display. Reaction time is affected by a number of variables and will be discussed in the following section. The qualitative movement pattern appears to be mainly related to three task variables: 1) angle of refixation, 2) new display's visibility, and 3) prior knowledge of the location of the new display. These three variables interact in ways related to limitations in peripheral vision, maximum extent of saccadic movements, and requirements for head movement. Figures 2, A through F, show illustrative qualitative changes related to these variables.

Fig 2A shows movement to a bright (clearly visible at initial location), certain location display at 30 degrees (from the initial display). One saccade of the correct extent is made, with no corresponding head movement. Since the original display is for a continuous control task it is returned to as rapidly as possible. Fig 2B shows the change that occurs with the same new display at 60 degrees. Head movement, with lower velocity and slightly delayed, is programmed along with the saccade. The new display is acquired only when the sum of the eye and head positions are at approximately 60 degrees. The length of the saccade in this illustration is typical of maximum lengths seen.

Fig 2C shows a 30 degree response with the displays spatial location (in the horizontal plane) unknown in advance (from among nine possible locations). There is no head movement and two distinct saccades occur, with a period of stationary fixation between them. In this case, even though the new display was bright enough to be seen easily from the original fixation point, prior uncertainty as to its location led to a less than adequate first saccade and a delay necessary to program and execute a second saccade of the correct amplitude. (The correct display was the only one lighted.)

Fig 2D shows movement to a 30 degree display that is both dim (cannot be detected at a 50 percent level at 30 degrees) and of uncertain location. Here, the lack of knowledge of the display's location, either from instructions or adequate brightness, led the operator to initiate head movement. (Many possible displays were beyond 40 degrees and thus would have required head movement.) A new phenomenon here is the occurance of a period of "dynamic fixation," or eye/head compensation between the two saccades. During this period, of approximately 150 msec, the eye moves back toward center with a velocity precisely matching the corresponding head velocity and thus keeping fixation stationary. In this case fixation was on the 20 degree display, a possible display that was then rejected with the execution of the second saccade to the 30 degree, correct display. This response also illustrates eye/head compensation after display acquisition, during which the eye returns to its central position while the head assumes almost all of the angle needed for display processing. This will occur more frequently if the display must be viewed for more than a few hundred milliseconds or if there is prior knowledge by the operator that the next display to be viewed is in another direction (not simply a return to the first as is illustrated here). Return of the eye to its central position is a rational control action since it provides maximum flexibility for subsequent saccadic movements.

Fig 2E shows a complex interposition of four saccades and three dynamic fixation (compensation) periods as a 60 degree display that is dim and of uncertain location is sought. Apparent fixations occur at the 20, 30, and 50 degree potential displays before the correct display is finally acquired.

Fig 2F shows the complexity that can occur if a dim display of uncertain location is at 90 degrees. Here there are seven fairly distinct saccades between six periods of dynamic fixation, including one decision to check a possible display location that had been bypassed by the initial saccade. This reversal decision also led to a temporary termination of head movement.

In all cases return to the original display was accomplished with one large saccade and appropriate head movement. The original display was comparatively bright and, of course, at a well-known location.

Figures 3 A and B show the systematic increase in both number of saccades and time for the total pattern of movements as a function of the three variables discussed above: 1) angle, 2) visibility (bright and dim), and 3) location certainty. (These data were taken from Robinson and Rath, 1976.) The similarity in form of these two measures reflects the fact that the time taken by each saccade and its succeeding dynamic fixation period is relatively constant.

REACTION TIME OF THE EYE

Prior to recent work it was widely agreed that reaction time for the eye (occularmotor latency) ranged from 150 to 200 msec and was minimally affected by most task variables such as display angle or visibility. (Robinson, Koth and Ringenbach, 1976, provide a brief overview of this position, including possible effects of alcohol [slight increase] and information processing after refixation [no effect].)

Interest in a more valid simulation of vehicle control led the author to construct a paradigm wherein an ongoing, continuous control task must be interrupted for the visual redirection to the peripheral display. This paradigm would seem to have fair generality. In systems where the operator is not engaged in continuous control they are, most likely, engaged in something when the command to refixate is received. Subsequent data shows that "something" need be very little to substantially increase reaction time.

"Interrupting something" has both quantitative and qualitative effects on the processes between command and first saccadic eye movement. The quantitative results show that the "classical" 150 to 200 msec result is unlikely in realistic settings and appears to be the result of a laboratory paradigm with the features: 1) simple, meaningless fixation light being extinguished as the command; 2) known location, clearly visible target; and 3) highly practiced, repetitive trials. In contrast, eye reaction times can reach 700 msec if an interrupted manual control task is felt to be more important than the peripheral display. Simply having the target appear randomly on the right or left--with the viewer knowing in advance which direction--can increase the reaction time to 350 msec. If the direction is not instructed in advance, and is presented symbolically as the command signal, the time will increase to approximately 500 msec. In neither of these cases is an ongoing task interrupted. If, on the other hand, there is an ongoing control task then the 350 msec will increase to 450 msec and the 500 will increase to 650 msec.

In summary, following a command to refixate the minimum delay is about 300 msec. Increases to 700 msec can result from combinations of directional uncertainty, symbolic as opposed to geometric (direct spatial) indicators of direction, and especially the existence and assumed importance of the ongoing or interrupted task. (This would <u>not</u> include the case where the operator might choose to delay refixation until satisfied with the status of ongoing control. Cases of this sort could be constructed wherein the operator might choose to wait 10 seconds--or 10 minutes!)

The qualitative change noted when a continuous task is interrupted is the occasional occurence of a period of eye/head compensatory movement <u>prior</u> to the first saccade toward the new display.

This behavior is rational since it permits the slower head to begin movement toward the new display, while the eye moves in the opposite direction and maintains fixation on the original display. This initial compensatory period, when it occurs, delays the eventual onset of the first saccade by 100 to 200 msec. The angle through which the compensatory movement occurs is usually less than 15 degrees and often only 5 or 10 degrees. Recent data in the author's laboratory indicate that some people compensate with the new display on the right or left side, some on one side only, and some never compensate. This would seem, therefore, to represent a learned phenomenon, albeit at a non-conscious level. Whether operators could be trained to use this strategy is not clear. (This same phenomenon has been observed in an automobile on the highway by Mourant and Grimson, 1977, who speculate that it may be a learned skill.) (A complete analysis of eye/head reaction time under these "realistic," engineering systems conditions is presented in Nelson, London and Robinson, 1978.)

It is appropriate to inquire as to the information processing relationship between the selection and programming functions for the eye and head going on during this reaction time and the processing of the display being interrupted. The question of overlap of these functions arises in relation to information processing theory and specifically to the limitations that may be imposed by the "single-channel" concept. No studies have yet directly examined this particular information processing issue. Two lines of evidence from the author's laboratory are relevant: 1) the longer reaction times when an ongoing task is interrupted (discussed above) and 2) the lack of evidence of any important deterioration in the continuous control performance during this period. In this case, it is possible that the requisite eye/head programming decisions are simply "squeezed in" during fairly quiescent control intervals. Some overlap would be predicted from the current theoretical position in that programming a saccade is a highly practiced task. Highly practiced tasks require little decision or memory capacity and may overlap other tasks. (An excellent introduction to human information processing and skill, with a distinct bias toward application, can be found in Welford, 1976.)

CHARACTERISTICS OF SACCADES

Saccades appear to represent a set of pre-programmed dynamic responses over which no effective control can be instituted once movement is initiated. Selection appears to consist only of a choice of the saccade's amplitude and direction but not of its velocity characteristics. For each individual a 20 degree saccade to the right will be remarkably stable in its average dynamic profile and will not be affected by any task variable outside those that might have major effects on all muscle systems. Referring to the range of variables illustrated in Fig 2, it is apparent that the individual saccades of the same extent are essentially the same over all conditions examined. Similarly, other variables such as motivation or preceived task importance have little if any effect on saccadic properties.

Typical position and velocity profiles for 25 and 40 degree saccades are shown in Fig 4. (Possible mechanisms and control systems producing these patterns are discussed by Robinson, D. A., 1968; Westheimer, 1954 a and b; and Yarbus, 1967.)

The control mechanism is not linear, with the important non-linearity for our purposes being a limited maximum velocity for saccades over about 20 degrees. This velocity is approximately 550 deg/sec, with college age people varying between 500 and 600 deg/sec. An individual will vary from one saccade to the next with a standard deviation of about 200 deg/sec.

A smaller saccade of 10 degrees will have a maximum velocity of 300 to 400 deg/sec. The average velocity for a 550 deg/sec maximum is about 300 deg/sec. Therefore, a 20 degree saccade will take approximately 67 msec and one of 40 degrees roughly double that, or 135 msec.

For refixations up to about 20 degrees one saccade will usually be executed. Between 20 and 40 degrees either one, or two saccades may occur. If there are two they appear to be programmed in advance and little time (less than 25 msec) will occur between them. For refixations over 40 degrees one or two saccades will be made out to a maximum extent of about 45 degrees where further travel must await movement of the head.

DYNAMIC FIXATION PERIODS

When the display location is not known in advance, and is not sufficiently visible in the periphery, saccades may be made to the possible display locations. If there is no corresponding head movement, as in Fig 2C, the eye will simply remain stationary until a subsequent saccade can be executed. However, if head movement has been initiated, it is necessary for the eye to compensate for that continuing movement in order to hold a stationary fixation. These periods of dynamic fixation are shown in Fig 2 D, E and F.

Although the eye is capable of compensating for head velocities up to 300 deg/sec, head movement may be slower during conditions favoring dynamic fixation periods. Values of head (and thus eye) velocities are typically in the range of 50 to 100 deg/sec. These periods last for 150 to 200 msec.

Two processes occur simultaneously during dynamic fixation periods: 1) fixation is stabilized for visual processing, and 2) the eye returns towards its central position, thereby allowing further large saccades.

The 150-200 msec time is minimum for simple rejection of a clear non-display. If determination of the correctness of a display required complex discrimination or choice then these processes would require more time than the 150-200 msec minimum. It appears that whatever processing is taking place in discriminating and rejecting the non-display is occuring to a large extent in parallel with the programming of the subsequent saccade; a situation similar to that noted above for the programming of the initial saccade (Reaction Time section).

HEAD MOVEMENT

Movement of the head may occur for any of three purposes: 1) the new display is located beyond the range of eye movement only (about 45 degrees); 2) the display to be processed will be retained, visually, for more than a fraction of a second; or 3) movement to other displays (not back to the point of beginning) is anticipated. For the first purpose the head will usually begin its movement before the termination of the first saccade, indicating that both are programmed in advance. The delay of the head after the initial saccade will range from 0 to 50 msec. The initial eye/head compensation period discussed under "Reaction Time," above, is an exception. When this behavior occurs the head will move 100 to 200 msec before the first saccade.

Head movements for the second and third reasons noted above have not been studied but, in any event, their presence probably does not affect overall performance times.

Head movement may occur with displays as close as 20 degrees but will not be frequent until about 30 and 40 degrees. Head movement will occur in almost 100 percent of all refixations over 45 degrees.

Average head velocities are shown in Fig 5 as a function of the same variables presented in Figures 3, A and B: 1) angle, 2) visibility, and 3) location certainty (data from London, Nelson, and Robinson, 1978). Displays bright enough to be detected prior to initiation of movement, or displays of certain location yield a linear increase in velocity with target angle. (This same linearity was shown by Robinson, Roth and Ringenback [1976] for maximum head velocity, up to 100 degrees). In all probability the velocities after 100 degree inter-display angles will level off. D. A. Robinson (1968) reports maximum (possible) head velocities of 300 deg/sec.

Displays of uncertain location, and insufficiently visible to be seen until fixation is within a few degrees, will not show the increase in velocity with angle (curve "D, U" in Fig 5).

The relatively large inter-subject difference reported by Robinson, Koth and Ringenback (1976) for maximum head velocities *do not* appear for average head velocities, which show a standard deviation over college age subjects of about 30 deg/sec.

Variability (standard deviation) within subjects averages to about 25 deg/sec for the DC, BC, BU data and 16 deg/sec for the DU condition (reference to Figs. 2 and 3). (The concerns expressed by Robinson, Koth, and Ringenback (1976) over the unpredictability of head velocities may have been related to their use of maximum values and due to the small subject population in their second experiment.)

DIRECTION OF REQUIRED REFIXATION

Little evidence is available on performance changes in eye or head movements as a function of direction of movement. Almost all wide angle research has been in or very near the horizontal plane. Yarbus (1967) suggests that the shape of a saccade may change slightly as they are directed in angles off the horizontal but he does not note any velocity differences. Measurements in the author's laboratory have indicated no differences in the reaction time for saccadic movement for any angle from horizontal to vertical. The lack of comment on this issue can probably be taken as indicating little effect, at least for small vertical angles. Larger vertical angles would require quite different head movement than horizontal ones. Since the maximum head velocities seen for most refixations are well below the maximum attainable head velocity there is little reason to assume that head dynamic behavior off of the horizontal plane is importantly different from that seen on the horizontal plane.

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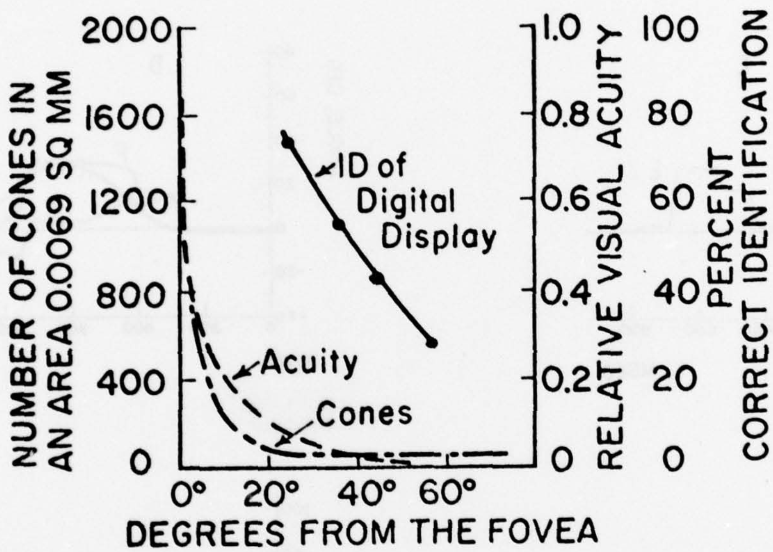


Figure 1

Distribution of Cones, Relative Visual Acuity, and Identification of a Digital Display as a Function of Degrees from the Fovea (Acuity and density data from Woodson, W. E. and Conover, D. W., Human Engineering Guide, Berkeley, Calif.: Univ. of California Press, 1964, 2nd Edit.; identification data from Koth, B. W. and Robinson, G. H., Peripheral discriminability of one-plane, rear-projection displays. Tech Rep 74-1, Dept. of Ind. Engr., University of Wisconsin, Madison, 1974.)

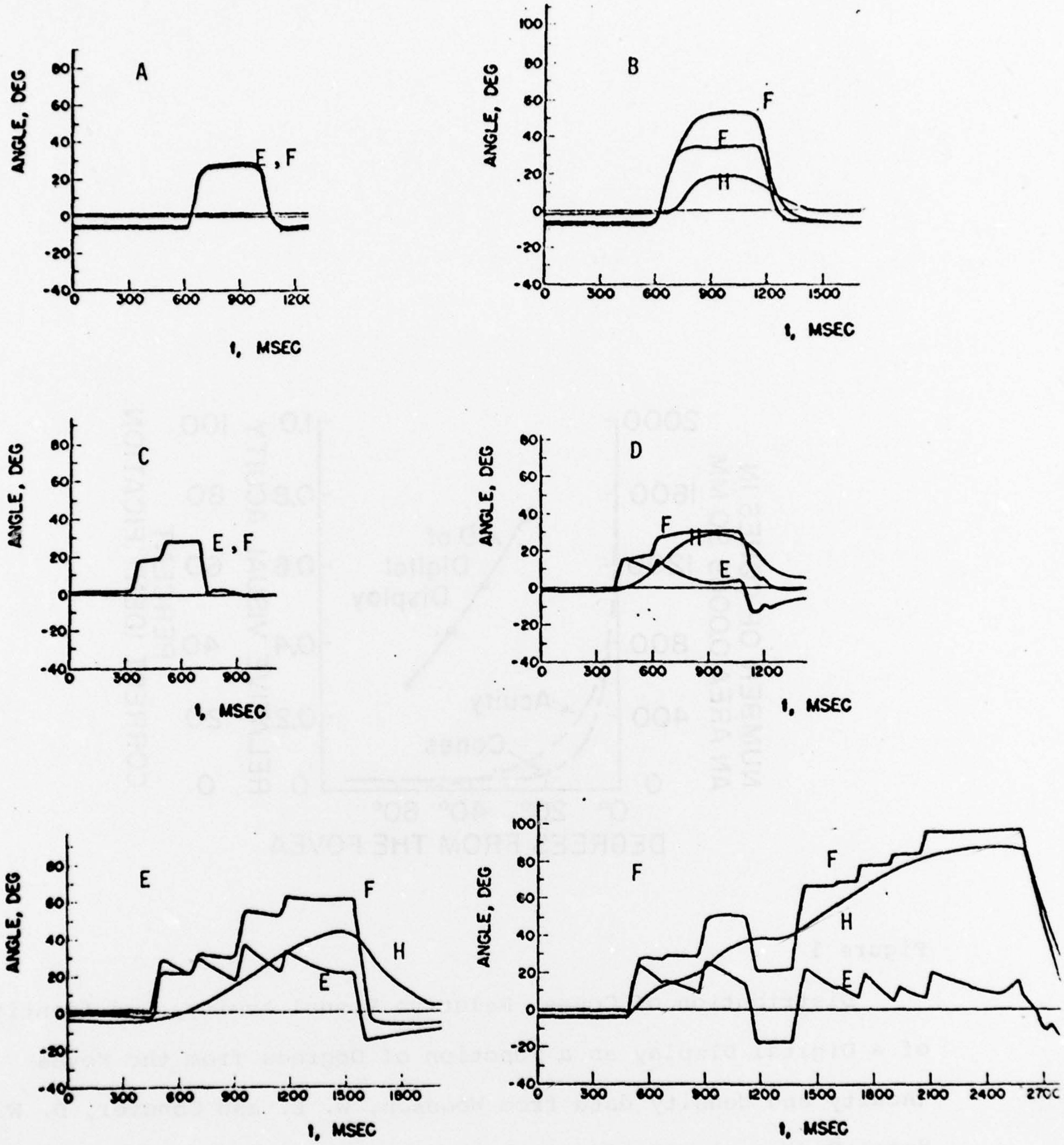


Figure 2

Eye and Head Responses to Commands to Refixate and Thereby Interrupt a Manual Control Task. (A) 30 deg, bright, certain location; (B) 60 deg, bright, certain location; (C) 30 deg, bright, uncertain location; (D) 30 deg, dim, uncertain location; (E) 60 deg, dim, uncertain location; and (F) 90 deg, dim, uncertain location. Command at t = 0. E - Eye, H - Head, F - Fixation. (Some responses begin at other than 0 deg, indicating the status of the display for the manual control task.) All displays at one meter distance in horizontal plane.

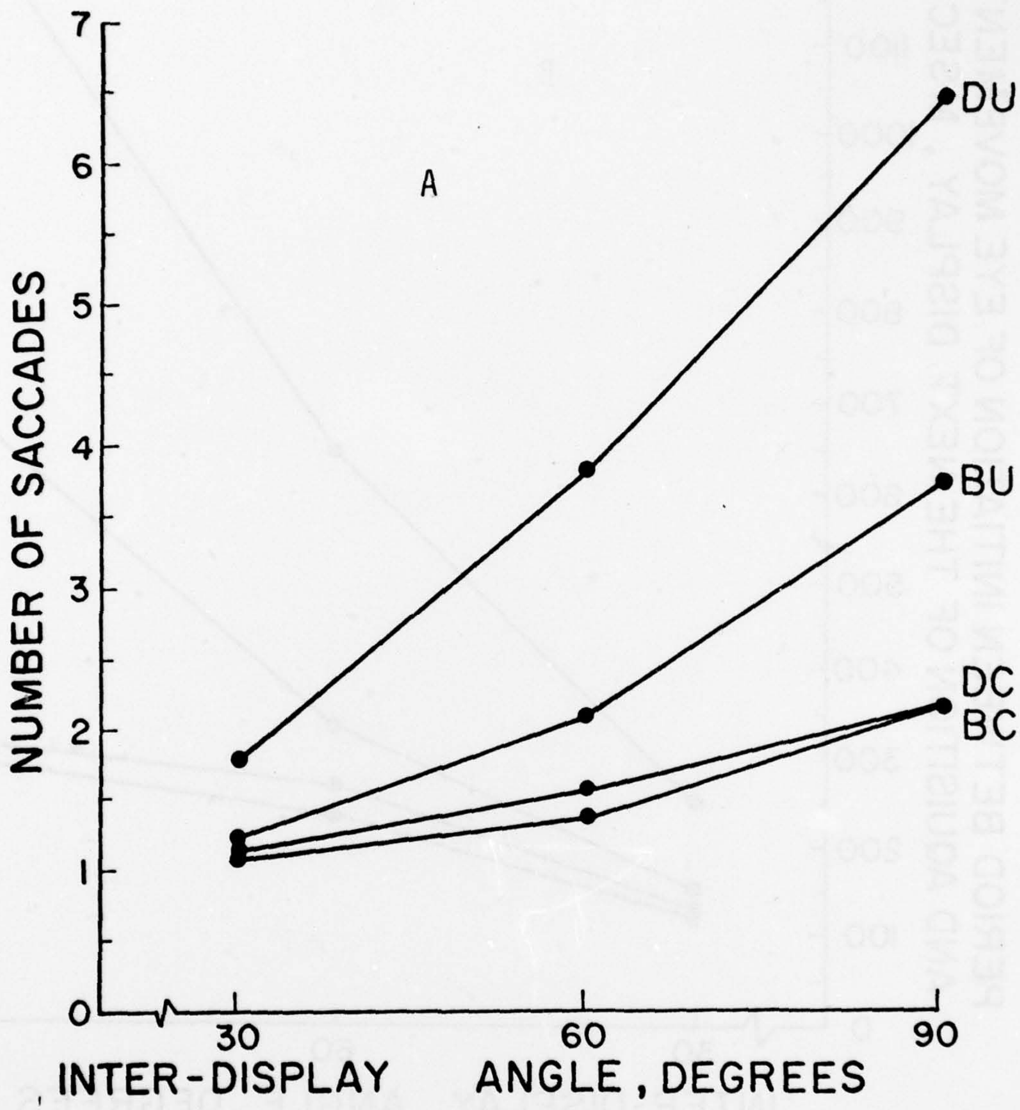
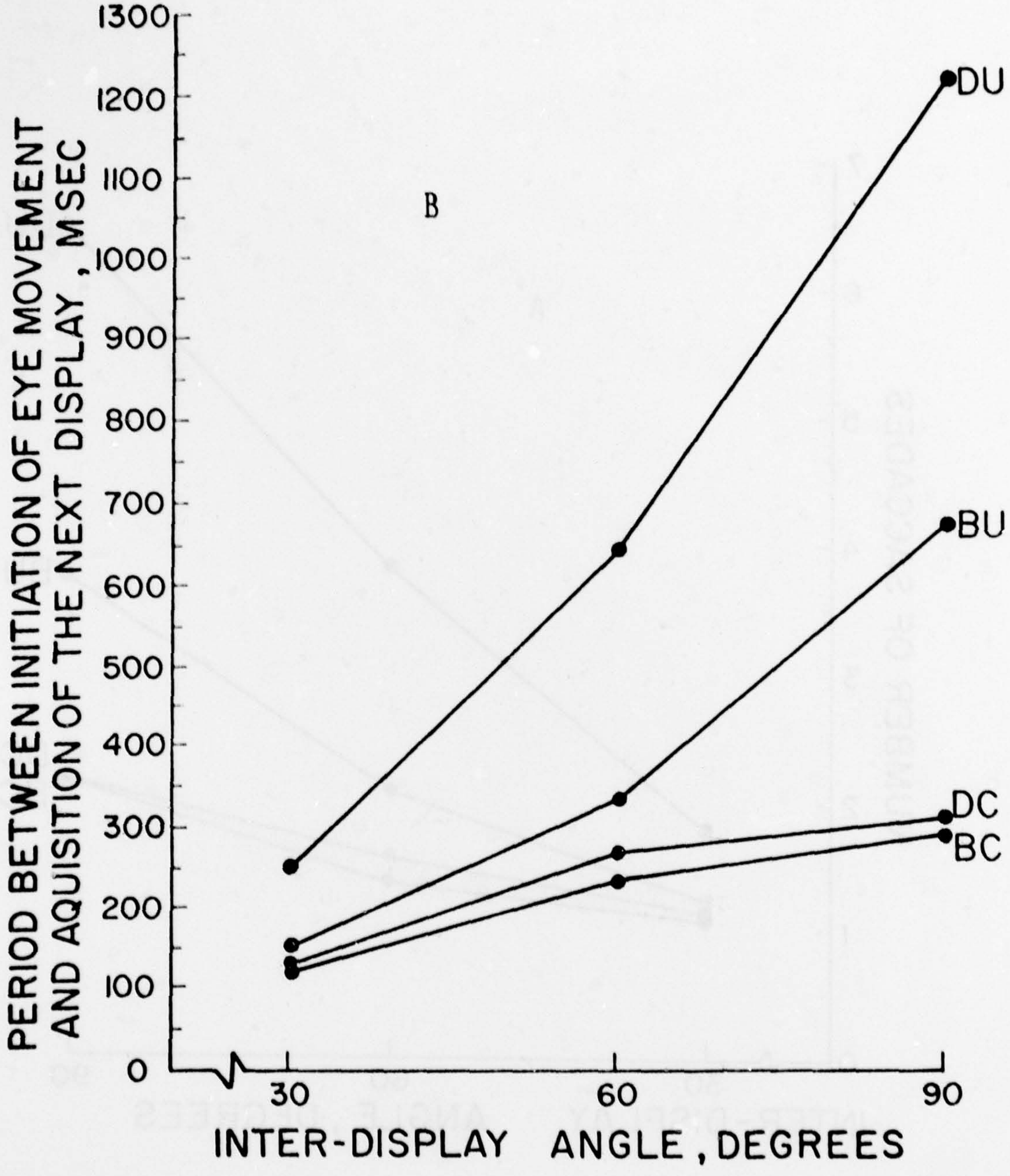


Figure 3

Number of Saccades (A) and Time Between Initiation of First Saccade and Subsequent Acquisition of the Next Display (B) as a Function of Inter-Display Angle. Display bright (B) or dim (D) and with known location (C) or unknown location (U). (Same parameters as in Fig 2.)


PERIOD BETWEEN INITIATION OF EYE MOVEMENT AND AQUISITION OF THE NEXT DISPLAY , MSEC
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INTER-DISPLAY ANGLE, DEGREES

Figure 3

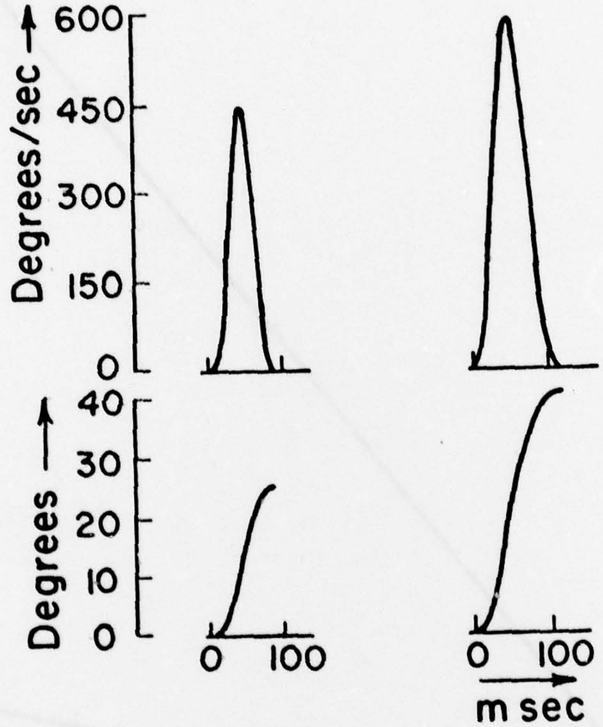

Figure 4

Illustrative Position and Velocity Patterns for a 25 Degree and 40 Degree Saccade. (One trial with one subject.)

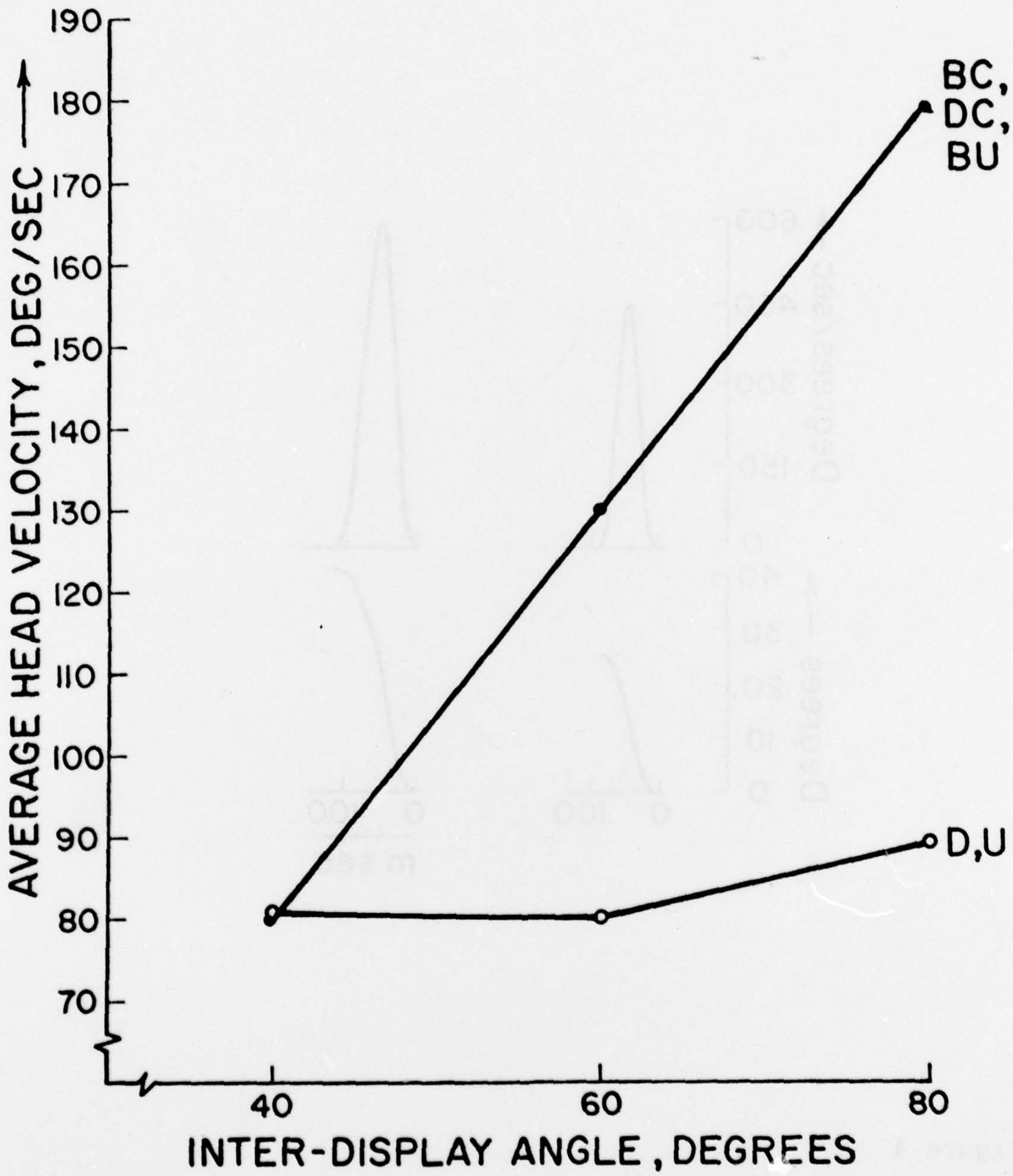

Figure 5

Average Head Velocity as a Function of Inter-Display Angle. Display bright (B) or dim (D) and with known location (C) or unknown location (U). (Same parameters as in Fig 2 and 3.)

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